Field, laboratory, and modeling investigation of the skin effect at wells with slotted casing, Boise Hydrogeophysical Research Site

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Abstract

Understanding and quantification of wellbore skin improves our ability to accurately measure or estimate hydrologic parameters with tests at wells such as pumping tests, flowmeter tests, and slug tests. This paper presents observations and results from a series of field, laboratory, and modeling tests which, together, explain the source of wellbore skin at wells at a research wellfield and which support estimation of skin thickness ($d_s$) and skin hydraulic conductivity ($K_s$). Positive wellbore skin effects were recognized at wells in the shallow, unconfined, coarse-grained fluvial aquifer at the Boise Hydrogeophysical Research Site (BHRS). Well development efforts at the BHRS removed residual drilling fines but only marginally reduced the skin effect. Likely causes for the remaining wellbore skin effect were examined; partial clogging of screen slots with sand is consistent with field observations and can account for the magnitude of wellbore skin effect observed. We then use the WTAQ code (Barlow and Moench, 1999) with a redefinition of the term for delayed observation well response to include skin effects at observation wells (in addition to pumping wells) in order to analyze aquifer tests at the BHRS for average $K_s$ values at individual wells. Systematic differences in $K_s$ values are recognized in results at pumping ($K_{s,Q}$) and observation ($K_{s,obs}$) wells: larger values are seen at observation wells (average $K_{s,obs} = 0.0023 \text{ cm/s}$) than pumping wells. Two possible causes are recognized for the occurrence of higher $K_s$ values at observation wells than pumping wells: (1) flow diversion between aquifer layers on approach to a pumping well with positive skin; and (2) larger portion of flow passing through lower-$K$ zones in the heterogeneous aquifer near the pumping well than the observation wells due to strongly radially convergent flow near the pumping well. For the well-aquifer system at the BHRS, modeling analyses of drawdown vs time at observation wells provide better $K_s$ estimates than those from pumping wells.

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Keywords: Wellbore skin; Well hydraulics; Modeling; Pumping tests

1. Introduction

Wellbore skin is a general term for imperfect hydraulic connection between a wellbore and the well structure and/or formation immediately outside the borehole. The imperfect connection may be due
to: drilling, construction, or other effects on the well structure; composition and structure of annular fill; and/or changes in the formation near the well during or following the drilling process. Wellbore skin acts as a filter in series between the borehole and the undisturbed formation. As such, wellbore skin causes either an additional resistance to flow (positive skin) if it has lower hydraulic conductivity ($K$) than the undisturbed formation (e.g., invasion of drilling mud into the formation; encrustation or sand-clogging of a well screen), or causes a lessened resistance to flow (negative skin) if it has higher $K$ than the undisturbed formation (e.g., sand or gravel pack in annular space).

Depending on the contrast in $K$ between wellbore skin and the formation, the presence of wellbore skin can influence the use of a well, and can cause drawdown measured in a pumping well to give misleading values of $K$. Examples include lost production or added cost for operation in order to overcome additional head loss to achieve a given flowrate. Understanding the causes and magnitude of wellbore skin permits evaluation of effects and consideration of options to mitigate or quantitatively account for effects. Also, inclusion of values for skin improves our ability to get accurate formation parameters from hydrologic well tests (van Everdingen, 1953; Ramey, 1970; Faust and Mercer, 1984; Moench, 1984; 1997; Dane and Molz, 1991; Molz et al., 1994; Butler, 1998; Young, 1998; Dinwiddie et al., 1999; Rovey and Niemann, 2001).

In this paper, we focus on the estimation of wellbore skin at the Boise Hydrogeophysical Research Site or BHRS (Fig. 1), a research wellfield that has been developed in a shallow, unconsolidated, coarse-grained fluvial aquifer (Barrash et al., 1999). Our interest in understanding and quantifying wellbore skin is to support subsequent investigations of heterogeneity of hydraulic parameters from hydrologic well tests at the BHRS. In this paper we: (a) describe the well construction method used at the BHRS and present evidence for positive wellbore skin; (b) examine causes for skin using field, laboratory, and modeling methods; (c) use our understanding of the cause for skin and a version of the WTAQ model (Barlow and Moench, 1999) that includes skin effects at observation wells, in addition to pumping wells, in order to analyze aquifer tests at the BHRS for skin hydraulic conductivity ($K_s$) values at individual wells; and (d) examine systematic differences in $K_s$ values at pumping and observation wells and determine that these differences may be due to the conceptual model-error associated with (1) treating the aquifer as a homogeneous (one-layer) system rather than a multi-layered system, and perhaps also with (2) the ‘pseudoskin’ effect, or lower effective $K$ in the immediate vicinity of a pumping well due to strongly convergent flow in a heterogeneous aquifer (Desbarats, 1992; Neuman and Orr, 1993; Rovey and Niemann, 2001).

### 2. Hydrogeologic setting and well construction

Field data for this paper are taken from the BHRS, which is located on a gravel bar adjacent to the Boise river 15 km east of downtown Boise, Idaho, USA. Eighteen wells were completed in the same manner (Fig. 2) within an 80 m $\times$ 60 m area (Fig. 1). General stratigraphy at the site is: coarse-grained unconsolidated fluvial deposits underlain by clay (Barrash and Reboulet, 2004). Wells were designed to: (a) support a wide variety of hydrologic and geophysical testing; (b) provide hydraulic communication to the formation.
throughout the saturated thickness of the unconfined fluvial aquifer; (c) maximize information gathered during the well construction process; and (d) minimize the volume of formation adjacent to the wells that may be disturbed by the drilling or installation processes (Barrash and Knoll, 1998).

Detailed information is provided here on well drilling, construction, and cleaning to support the understanding of wellbore skin at wells at the BHRS. Well materials that were used to meet the above-mentioned design criteria are (Fig. 2): 10 cm ID, 11.43 cm OD, schedule 40, PVC casing above the water table and below the fluvial aquifer; and 10 cm ID, 11.43 cm OD, schedule 40, PVC slotted casing (0.05 cm slot aperture) throughout the saturated thickness of the fluvial aquifer. The well construction and emplacement methods used were: (a) coring through the full thickness of the fluvial aquifer by driving a 0.6 m long, 6.03 cm diameter split spoon; (b) drilling with a 9.84 cm diameter bit following each 1.2 m of new coring; (c) using only synthetic (non-biodegradable) drilling mud; (d) driving 12.7 cm ID, 13.34 cm OD, steel casing with 15.24 cm OD drive shoe to new cored and drilled depths to hold back the formation—and also to hold back drilling cuttings from the borehole column prior to renewing coring; (e) drilling 1.5–3 m into the clay layer underlyng the fluvial aquifer; (f) flushing the column with clean water; (g) setting the PVC screen and casing; and (h) pulling out the steel drive casing to allow collapse of the formation against the PVC screen and casing. Largey similar drilling and construction methods used by Morin et al. (1988) in sandy unconsolidated sediments and by Rehfeldt et al. (1989) in unconsolidated sand and gravel sediments were shown to produce a smaller radius of disturbance than wells that were augered or drilled with conventional mud (e.g. bentonite) and that were then stabilized with filter packs after drilling.

Initial well development following well installation was minimal. Approximately 0.47 L of common bleach (active ingredient: Na-hypochlorite) was added to each well to decompose the synthetic drilling mud to dissolved components. A surge block was moved down the well very slowly to distribute the bleach through and immediately outside the full length of saturated screened interval. Also, sand that had entered each well upon removal of the drive casing was pumped from the bottom of each well.

3. Evidence of wellbore skin

Positive wellbore skin causes excess drawdown in a pumped well compared to predicted drawdown based on hydraulic parameters determined from observation wells. Such wellbore skin effects were recognized in results from a fully penetrating pumping test conducted at the BHRS in 1998 with multiple fully penetrating observation wells (Fig. 3). For this test, well A1 was pumped at 171 L/min and drawdown was recorded in wells at radial distances of 3.6–40.1 m from A1. Type-curve matches to drawdown behavior at observation wells yielded similar aquifer parameters from analyses treating the aquifer as unconfined, homogeneous, and anisotropic (Table 1) using the WTAQ analytical model (Barlow and Moench, 1999). However, attempts to match the drawdown behavior of the pumping well with aquifer
parameters similar to those determined for the observation wells were not successful. In particular, drawdown in the pumping well (A1, see Fig. 1) was 0.6 m greater than expected (Fig. 3). Here we note that approximately half of the excess drawdown from the 1998 test may be attributed to turbulent well loss leaving about 0.3 m of excess drawdown that was not due to either formation (i.e. hydraulic head) loss or turbulent well loss. Fig. 4 shows step drawdown results for well A1 at the BHRS for seven pumping rates between 38 and 170 L/min. Each pumping test was conducted as a separate test. Drawdowns are compared at the same elapsed time of pumping (20.5 min). It is evident that: (a) drawdown per unit pumping rate is constant (i.e. no indication of non-linear well losses) to 114 L/min and then increases with increasing pumping rate.

Parameters defined in text.

Table 1
Aquifer test data and results from curve-matching using the WTAQ code (Barlow and Moench, 1999) with pumping at 171 L/min from well A1 (prior to well cleaning) on October 22, 1998 and with aquifer thickness of 15 m (also see Figs. 1–3).

<table>
<thead>
<tr>
<th>Well</th>
<th>(r) (m) from A1</th>
<th>(K_r) (cm/s)</th>
<th>(K_z) (cm/s)</th>
<th>(S_y) (m(^{-1}))</th>
<th>(S_{y0}^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B5</td>
<td>3.61</td>
<td>0.07</td>
<td>0.035</td>
<td>0.0001</td>
<td>0.03</td>
</tr>
<tr>
<td>C2</td>
<td>8.17</td>
<td>0.08</td>
<td>0.05</td>
<td>0.0001</td>
<td>0.03</td>
</tr>
<tr>
<td>X4</td>
<td>22.1</td>
<td>0.06</td>
<td>0.025</td>
<td>0.00013</td>
<td>0.15</td>
</tr>
<tr>
<td>X3</td>
<td>30.03</td>
<td>0.075</td>
<td>0.03</td>
<td>0.00013</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Parameters defined in text.

\(^a\) Anomalously low \(S_y\) values from analytical modeling of aquifer tests have been reported by numerous workers (e.g. Neuman, 1975; Moench, 1994; Chen and Ayers, 1998).
4. Possible causes for wellbore skin in wells at the BHRS

Given the positive skin effect observed in pumping test results, we examine possible causes for skin with the expectation that an understanding of the cause could provide options for removal, mitigation, and/or quantification of skin dimensions and magnitude. In this section, we consider the following possible causes: (1) compaction of the formation during the drilling and well construction processes; (2) invasion of the formation adjacent to the wells with residual synthetic drilling mud and fine cuttings from the drilling process; (3) head loss due to the well screen and blockage of entrances at the margin of the well screen; and (4) head loss due to partial sand-clogging of the well screen itself.

4.1. Possible compaction of the formation during well drilling and construction

As noted above in Section 2, the formation was held behind 13.34 cm OD drive casing during the drilling process. The question may arise as to whether the formation was compacted in the process and did not collapse against the slotted casing during well construction. In such a scenario, compacted material might cause or contribute to a positive skin effect. However, there are several reasons why compacted formation without collapse probably did not occur much at the BHRS wells. As noted above, a 15.24 cm OD drive shoe was welded to the bottom of the drive casing and we observed that sand invaded the screen of each well with removal of the drive casing indicating collapse against the screen for each well upon withdrawal of the drive casing. The drive casing was not removed easily and the considerable jerking and vibration during drive casing removal with the oversize drive shoe undoubtedly contributed to formation collapse as well. Also, geophysical testing for vertical seismic profiles of each well using a geophone pressed against the inner borehole wall with a bowspring indicated good mechanical coupling to the formation through the well screen (Michaels, 1998; 2001) and generated complete profiles without intervals of ringing or highly attenuated and noisy signals that would indicate zones of poor collapse (Dr P. Michaels, 2001, personal commun.). Also, the vast majority of the aquifer is cobbles and sand (Barrash and Reboulet, 2004) with framework cobbles which are not likely to compact and cause significant decrease in K in the same sense as more ‘pliable’ sands or finer-grained sediments might. Undoubtedly there are local places with incomplete collapse but these are not the norm or pervasive.

4.2. Possible invasion of the formation with drilling residues

Although care was taken in the drilling process to minimize escape of drilling mud and fine cuttings into the formation adjacent to the well (see Section 2 above), such invasion could occur to some degree during drilling between advancements of the drive casing. Also, initial efforts to remove residual drilling mud after well construction were not aggressive and likely influenced only a small radial distance outside a given well. Aggressive well development with surging has been recommended following well construction with the drive-and-wash method used here (Rehfeldt et al., 1989; Molz et al., 1994; Young, 1998), but we wanted to minimize rearrangement of grains in the formation to the extent possible. However, once skin was recognized, a series of additions of bleach and energetic surging were conducted at well C2 at the BHRS to determine if skin effects could be reduced and possibly removed in this manner. In this process, each addition and surging cycle was followed by a pumping test at C2 conducted at a similar pumping rate and with the same observation wells. Resulting skin effects were compared with those from a pre-treatment pumping test conducted for base performance characteristics prior to well development. The skin effect as measured by the dimensionless skin parameter of Moench (1997) is:

\[
F_s = \frac{K_s d_s}{r_w K_r}
\]

where \(K_s\) is skin hydraulic conductivity, \(d_s\) is skin thickness, \(K_r\) is radial hydraulic conductivity of the aquifer, and \(r_w\) is the radius of the pumping well at the screen. In this manner, a series of three aggressive surging treatments throughout the full-screened section of well C2 were conducted. The skin effect
was reduced ~30% by the first two treatments, but was not reduced further with a third treatment.

Considering the significant amount of remaining skin effect and the potential for affecting the porosity and permeability structure in the formation outside the wells with repeated aggressive surging, other wells were treated only with slow surging sufficient to mobilize residual fine cuttings. This process was monitored by observing dark material (mobilized fines) passing to the pump through the partially translucent intake hose. Slow surging was continued at each successive 1.5 m depth interval until the discharge clarified—usually requiring only a few minutes of surging per interval. Post-surging pumping tests showed only small reductions in drawdown or skin magnitude. With the removal of residual fines accomplished by slow surging but still having significant skin effect, we concluded that the remaining skin effect is largely due to causes other than drilling residues left in the formation. That is, we now focus our investigation on the well screen to examine head loss and quantify wellbore skin. In this regard, we take the radial thickness or radial width of the skin zone, \( d_s \), to be equal to the wall thickness of the well screen, 0.635 cm.

### 4.3. Possible head loss due to screen or to blockage of screen entrance

Reconnaissance laboratory experiments were conducted to measure head loss associated with flow through the well screen (alone and with partial blockage of the entrance to the well screen) to determine if flow resistance at the well screen could account for the magnitude of additional drawdown caused by the skin effect at wells at the BHRS (e.g. ~0.06–0.4 m additional drawdown at pumping rates of ~62–114 L/min over ~15 m of saturated screened interval). For these experiments, screen sections were placed in constant head water reservoirs while pumping, successively, at a series of constant rates inside the screen to determine head loss across the screen. Results (Table 2) indicate that head loss due to the screen alone is several orders of magnitude less than was observed in the field (e.g. Fig. 3) for pumping rates comparable to, or considerably greater than, those used in the field. For perspective on these results, we can calculate expected head loss across the screen using a fracture-flow conceptual model for the well screen.

Slotted PVC casing used in wells at the BHRS (Fig. 5A) has sets of factory-milled horizontal grooves with 0.05 cm aperture, which is the upper diameter of medium sand (Pettyjohn et al., 1973). Each groove is offset vertically from the next by 0.318 cm of blank casing. For a given 3 m section of slotted casing, ~0.15 m is left blank at either end to provide mechanical strength where sections are screwed together (Figs. 2 and 5A). Also, horizontal grooves are interrupted by six vertical segments of blank casing at 60° radial intervals for mechanical strength such that ~72% of the screen circumference is slotted and ~28% is blank.

<table>
<thead>
<tr>
<th>Pumping rate (L/min)/m of screen</th>
<th>Fracture model predicted drawdown (m)</th>
<th>Experimentally observed drawdown (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.4</td>
<td>0.00021</td>
<td>–</td>
</tr>
<tr>
<td>37</td>
<td>0.00061</td>
<td>0.00067</td>
</tr>
<tr>
<td>74.5</td>
<td>0.00122</td>
<td>0.00168</td>
</tr>
<tr>
<td>112</td>
<td>0.00171</td>
<td>–</td>
</tr>
<tr>
<td>149</td>
<td>0.00247</td>
<td>0.00213</td>
</tr>
<tr>
<td>199</td>
<td>0.00335</td>
<td>0.00396</td>
</tr>
<tr>
<td>248</td>
<td>0.00396</td>
<td>0.00594</td>
</tr>
<tr>
<td>298</td>
<td>0.00488</td>
<td>0.00655</td>
</tr>
</tbody>
</table>

Overall, this geometry results in <10% porosity for the slotted sections; this porosity is less than the range of ~12–50% porosity in the fluvial sediments at the BHRS (Barrash and Clemo, 2002). However, with respect to hydraulic behavior, slotted casing is more like a fractured medium than a porous medium. Using the slot aperture and spacing geometry given above, and calculating \( K \) for each screen slot as if it were a fracture between two smooth parallel plates.
Then:

\[ K = \frac{b^2 \rho g}{12 \mu} \equiv 19 \text{ cm/s} \]  

(2)

for an individual fracture where \( b \) is the fracture or slot aperture, \( \rho \) is water density, \( g \) is gravity, \( \mu \) is dynamic viscosity, and water is at 15.5 °C. Upscaled \( K \) for a set of such fractures (e.g. Snow, 1968; Moench, 1984), with each separated by 0.318 cm of impermeable blank PVC casing from the next fracture above or below, is 2.6 cm/s (Fig. 5B). Then, accounting for 28% of the screen circumference in blank casing, upscaled screen \( K \) becomes 1.87 cm/s.

Knowing the inside and outside diameters of the slotted casing (\( r = 5.08 \text{ cm} \) and \( R = 5.72 \text{ cm} \), respectively), the pumping rate \( Q \) per length of screen \( (\Delta z) \), and upscaled \( K \) for the screen, and then imposing a constant head \( (H) \) boundary outside the screen, we can use the Theim equation:

\[ h(r) - H(R) = \frac{Q}{2\pi K \Delta z} \ln \frac{r}{R} \]  

(3)

(e.g. deMarsily, 1986) to estimate drawdown due to the screen alone (Table 2). Results predicted by the slot fracture conceptual model are similar to those measured in the laboratory cell, with departures from the model (i.e. higher measured head loss) occurring at flow rates \( > 200–250 \text{ (L/min)/m of screen} \) (Table 2). Here we note that Eq. (3) does not account for non-linear head losses at the higher pumping rates.

To examine (on an order-of-magnitude basis) whether partial blockage of flow at the entrance to the screen would significantly increase head loss to magnitudes similar to those observed in the field, laboratory pumping tests were conducted with 40 and 60% of the open slot circumference blocked by strips of tape, and also by an undetermined percentage of blockage due to grains of fine gravel (average diameter \( \sim 4 \text{ mm} \)) glued against the blank casing and positioned such that they were in contact with each other and centered across the slots. These tests were run at pumping rates between 37 and 298 (L/min)/m of screen. For comparison, total pumping rates of \( \sim 62–171 \text{ L/min during field tests at the BHRS are equivalent to } \sim 4.1–11.4 \text{ (L/min)/m of screen length for } \sim 15 \text{ m of screened saturated thickness. Results from these experiments (Fig. 6) indicate that: (a) aggregate screen } K \text{ may be approximated as a medium with a regular fracture-set geometry; (b) } K \text{ of slotted casing is approximately } 1.9 \text{ cm/s, which is higher than } K \text{ of any units in the unconsolidated fluvial deposits at the BHRS; and (c) partial blockage of the outer edge of the screen is an insufficient cause for the } \sim 0.06–0.4 \text{ m of excess drawdown attributable to wellbore skin at the BHRS.}
4.4. Possible head loss due to sand within screen slots

The remaining plausible cause for the wellbore skin effect in wells at the BHRS is partial clogging of screen slots due to invasion of sand grains. With the slot aperture the same dimension as the upper diameter of medium sand, invasion to some degree is likely to occur in the absence of a graded filter pack outside the well. Grain-size analyses of core from wells at the BHRS include fine to medium sand as part of the textural composition throughout the fluvial section (Reboulet, 2003). As noted above (Section 2), we know that sand passed into each of the wells at the BHRS during installation (i.e. with collapse of the formation against the screen during removal of the drive casing). It is reasonable to suppose that some sand grains remain in screen slots because they are wedged there or are resting in storage between transport events. And indeed some sand grains have been observed at the inner margin of slots in video logs of wells at the BHRS. In this section, we use numerical modeling experiments to examine if head losses associated with partial clogging of screen slots with sand might cause the magnitude of additional head loss observed during pumping tests at the BHRS.

4.4.1. Numerical modeling of head loss through partially clogged screen slots

To evaluate head loss through the screen due to reduced $K$ per screen slot caused by partial clogging, an axisymmetric layered model was constructed using a modified version of MODFLOW-2000 (McDonald et al., 1988; Harbaugh et al., 2000) with: (a) a segment of slotted casing having the same radial and vertical geometry as slotted casing used in wells at the BHRS; (b) partially sand-clogged slots treated as granular aquifers that are separated from each other by blank screen sections treated as aquicludes (Fig. 7A); (c) a very high-$K$ reservoir region outside the well screen that is bounded with constant head nodes; and (d) explicit treatment of the wellbore with very high $K$. Such explicit treatment in MODFLOW of a well with lateral variations of $K$ in a layered axisymmetric system (Clemo, 2002) was developed to examine skin effects on well and near-well hydraulics (Clemo and Barrash, 2003).

Model results are given in Fig. 7B for drawdown on passage through partially sand-clogged screens having individual slot $K$ values ranging from 0.14 to 0.0014 cm/s (average screen $K$ of 0.019–0.00019 cm/s, respectively), and having equivalent pumping rates for fully penetrating pumping tests that range from 38 to 189 L/min at BHRS wells. To get head losses of approximately 0.3 m at 114 L/min, $K$ values for individual partially sand-filled screen slots treated as aquifers are $\sim 0.005$ cm/s per slot (Fig. 7). This $K$ value for individual partially sand-filled screen slots is in the middle of the range of values for aquifers consisting of clean sand (e.g. Freeze and Cherry, 1979), or in the mid-to-upper part of the range for medium sand (e.g. Domenico and Schwartz, 1998). The equivalent average $K$ value for the screen is $\sim 0.0007$ cm/s. It appears then that partial sand-clogging of screen slots provides a plausible mechanism to cause, excess head loss of the magnitude observed in fully penetrating pumping tests at the BHRS.

5. Evaluation of skin with analytical modeling of aquifer tests

We can now evaluate average $K_s$ values per well using analytical modeling to match results from fully
penetrating pumping tests. Because there are a number of closely spaced wells that are used alternately as pumping and observation wells, we include effects of wellbore skin at observation wells in the WTAQ code (Barlow and Moench, 1999) so we can then examine the consistency of wellbore skin results for a given well from a number of tests. Given that systematic differences between \( K_s \) at pumping wells \( (K_{s,Q}) \) and at observation wells \( (K_{s,obs}) \) result from this analytical modeling, we next consider two possible causes for additional head losses at pumping wells vs observation wells: (1) vertical flow divergence due to positive skin in a layered system and (2) strongly radially convergent flow effects in a heterogeneous system. We use modeling to show that the magnitude of the effect of vertical flow divergence is similar to (but in some cases perhaps less than) the difference between \( K_{s,Q} \) and \( K_{s,obs} \). For this modeling, only results from aquifer tests at the BHRS with pumping rates \( \leq 114 \text{ L/min} \) are analyzed because these tests include formation and wellbore skin effects but likely do not include additional non-linear head losses (Fig. 4). The effect due to radially convergent flow is considered below but the magnitude is difficult to evaluate without detailed knowledge of the heterogeneous \( K \) structure in the region affected by the pumping test.

Fig. 7. (A) Schematic cross-section of wall of PVC well screen with sand invasion into 0.05 cm slot apertures treated as repeated layers of aquifers and aquicludes. (B) Drawdown vs \( K \) per individual screen slot (i.e. each partially sand-clogged slot treated as an aquifer in the model) at pumping rates scaled to be equivalent to rates in fully screened wells with 15 m of saturated thickness (i.e. as at the BHRS).

Fig. 8. Schematic diagram of pumping and observation wells with positive wellbore skin. \( L \) is screen length; \( K_r \) is hydraulic conductivity of the wellbore skin; \( d_s \) is radial thickness of wellbore skin; \( K_a \) is aquifer hydraulic conductivity; and \( h \) is head in the aquifer immediately adjacent to the wellbore skin. See Eq. (4) for statement of flow balance at the observation well. Not to scale.
5.1. Analytical model with observation well skin

The WTAQ analytical modeling code (Barlow and Moench, 1999) includes the capability to simulate wellbore skin effects at a pumping well. Here we include the capability to also simulate wellbore skin effects at observation wells as an independent check because we model drawdown behavior at a number of wells which are alternately used for pumping and observation.

The basis for analyzing wellbore skin at an observation well may be stated mathematically in terms of the head and flow balances that must occur at the interface between the aquifer and the skin that surrounds the well (Fig. 8):

\[ \pi r_{obs}^2 \frac{d h_{obs}}{dt} = 2 \pi r_{obs} L K_s \frac{(h-h_{obs})}{d_s} \]

where \( r_{obs} \) is the radius of the observation well; \( h_{obs} \) is measured head in the observation well; \( h \) is head in the aquifer; and \( L \) is the length of open screen. This condition may be included as a redefinition of the term for delayed observation well response in the existing WTAQ formulation (Barlow and Moench, 1999) which is solved with dimensionless parameters in the Laplace domain (see Appendix A) and then numerically inverted with the Stehfest (1970) algorithm.

Wellbore skin effects on drawdown behavior are different at pumping and observation wells (e.g. Fig. 9, see also Fig. 7 in Moench, 1985). For positive skin, additional drawdown occurs at the pumping well to drive the required flow rate through the skin or low-\( K \) filter zone between the aquifer and the well. This effect occurs throughout the pumping period. At the observation well, the low-\( K \) filter zone causes a delay in the equilibration of head between the observation well and the surrounding aquifer. This effect is most pronounced at the early time of observation well response, especially as seen in log-log plots of drawdown vs time (Fig. 9).

5.2. Results at pumping and observation wells

WTAQ was used to determine \( K_s \) and aquifer parameters from pumping tests run in 1999 at the BHRS after well cleaning was performed to remove residual synthetic drilling mud and drilling fines (see Section 2). \( K_s \) and aquifer parameter results from nine tests run at \( \leq 114 \) L/min at A, B, and C wells in the central portion of the BHRS (Fig. 1) are given in Table 3 (Fox, in prep.). For these analyses, curve matches were generated by forward modeling in a sequential process using known inputs for pumping rate and aquifer thickness while varying \( K_s \), \( S_s \), \( S_y \), and wellbore skin by trial and error at a given pumping and observation well (i.e. one pair of wells at a time).

Initially estimates for \( K_s \), \( S_s \), and \( S_y \) came from analysis of aquifer tests at observation wells without consideration of skin at either the pumping well or observation wells (e.g. Fig. 3, Table 1). Then, a curve match was obtained at a given pumping well using WTAQ with the inclusion of the pumping well skin effect and starting values for \( K_s \), \( S_s \), and \( S_y \) from the initial curve-matching step. Next, curve matches were obtained with the inclusion of skin values at the observation well using \( K_{s,Q} \) from the previous step as the initial estimate for \( K_{s,obs} \). It soon was recognized that highly variable and, commonly, unrealistically low \( S_s \) values were required to obtain matches at observation wells if \( K_{s,obs} \) values were forced to be the same as \( K_{s,Q} \) values from the previous step. However, \( S_s \) is not expected to vary widely or have unusual values in the small volume of coarse fluvial
Table 3
Screen K and aquifer parameter values from analytical modeling

<table>
<thead>
<tr>
<th>Well</th>
<th>A1</th>
<th>B2</th>
<th>B3</th>
<th>B4</th>
<th>B5</th>
<th>B6</th>
<th>C3</th>
<th>C5</th>
<th>C6</th>
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<td>113</td>
<td>112</td>
<td>110</td>
<td>111</td>
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<td>5</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>5</td>
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<tr>
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<td>$1.05 \times 10^{-3}$</td>
<td>$8.5 \times 10^{-4}$</td>
<td>$5.0 \times 10^{-4}$</td>
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<td>$1.0 \times 10^{-3}$</td>
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<td>0.05</td>
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<td>0.05</td>
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<td>0.05</td>
<td>0.05</td>
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<td>0.075</td>
</tr>
<tr>
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<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.13</td>
<td>0.095</td>
<td>0.075</td>
</tr>
<tr>
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<td>$3.3 \times 10^{-5}$</td>
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<td>$3.3 \times 10^{-5}$</td>
<td>$3.3 \times 10^{-5}$</td>
<td>$3.3 \times 10^{-5}$</td>
</tr>
<tr>
<td>Max $s_s$ (m$^{-1}$)</td>
<td>$1.3 \times 10^{-4}$</td>
<td>$8.2 \times 10^{-5}$</td>
<td>$3.3 \times 10^{-5}$</td>
<td>$3.3 \times 10^{-5}$</td>
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<td>$9.8 \times 10^{-5}$</td>
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</tr>
<tr>
<td>Ave $s_y$</td>
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<td>0.03</td>
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<td>0.02</td>
<td>0.02</td>
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<td>0.034</td>
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<tr>
<td>Min $s_y$</td>
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<td>0.015</td>
<td>0.017</td>
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<td>0.017</td>
<td>0.017</td>
<td>0.030</td>
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<td>Max $s_y$</td>
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<td>0.06</td>
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<td>0.03</td>
<td>0.04</td>
<td>0.066</td>
<td>0.03</td>
<td>0.04</td>
</tr>
</tbody>
</table>

*a* $n_{o,a}$ refers to the number of observation wells paired with a given pumping well from one pumping test.

*b* $n_{o,b}$ refers to the number of pairings of a given well as an observation well with different wells as pumping wells (i.e. during $n_{s,Q}$ different pumping tests).

*c* Not all pumping-observation well pairs exhibited anisotropic behavior but, for simplicity here, average values include results from all well pairs.

*d* Anomalously low $s_y$ values from analytical modeling of aquifer tests have been reported by numerous workers (e.g. Neuman, 1975; Moench, 1994; Chen and Ayers, 1998).

Aquifer under study at the BHRS (Fig. 1). So, in the final step, curve matches are obtained for a given pumping well-observation well pair by (a) allowing $K_{s,obs}$ to be greater than $K_{s,Q}$ while (b) all other aquifer parameters are the same for the pumping and observation well (Table 3). A reasonable starting value for $s_s$ in this last step is $3.3 \times 10^{-5}$ m$^{-1}$, considering the discussion above as well as expected values for $s_s$ in this type of aquifer (e.g. Domenico and Schwartz, 1998, Table 4.1).

Several patterns are evident from the $K_s$ results presented in Table 3: (a) in all but one case, $K_s$ values at observation wells are higher than at pumping wells, and generally they are $\sim 1.5–5$ times higher; (b) $K_{s,obs}$ values from matches at individual observation wells are similar (average $K_{s,obs}=0.0023$ cm/s); and (c) $K_{s,Q}$ values from matches at individual pumping wells have a wider range overall than for observation wells. Although the magnitudes of differences between and among $K_s$ values for pumping or observation wells are not great overall, relatively small differences in $K_s$ can result in significant differences in drawdown behavior (e.g. Fig. 7B).

5.3. Possible causes for higher $K_s$ values at observation wells than pumping wells

We now consider why $K_s$ values at observation wells are, with only one exception, greater than $K_s$ at pumping wells from analytical modeling of field data.
at pumping well-observation well pairs. Such systematic differences may occur if drawdown at a pumping well includes other head loss effects beside formation and screen losses that are not active or not as pronounced at observation wells. Here we are excluding non-linear entrance losses because we are analyzing BHRS pumping tests run at ≤114 L/min (Table 3). Two possible causes are recognized for the occurrence of lower $K_s$ values at pumping wells than observation wells: (1) flow diversion between aquifer layers on approach to a pumping well with a positive skin (Young, 1998; Halford, 2000; Clemo and Barrash, 2003); and (2) larger portion of flow passing through lower-$K$ zones near the pumping well in a heterogeneous aquifer than at observation wells due to strongly radially convergent flow near the pumping well (Desbarats, 1992; Neuman and Orr, 1993; Rovey and Niemann, 2001). These two possible causes for lower $K_s$ values at pumping wells are discussed below.

5.3.1. Possible additional head loss due to flow diversion in a layered system

Here it is important to note that the WTAQ model assumes a homogeneous (one-layer) aquifer system, but the aquifer at the BHRS is a four- or five-layer system (Barrash and Clemo, 2002; Barrash and Reboulet, 2004). Vertical flow diversion can occur between layers in the vicinity of a pumping well with positive skin in layered aquifer systems (Fig. 10) (Young, 1998; Halford, 2000; Clemo and Barrash, 2003). The positive skin zone decreases effective $K_r$ near the well for all layers because the relatively lower $K_s$ acts in series with the relatively higher $K_r$ of either higher- or lower-$K_r$ layers. In detail, the effective $K_r$ values adjacent to the wellbore at relatively high-$K_r$ layers are reduced more (due to harmonic averaging of $K_s$ and high-$K_r$ in series) than are effective $K_r$ values at relatively lower-$K_r$ formation layers. That is, a net effect of the positive skin zone (i.e. low-$K$ filter in series with each aquifer layer) is to distort the near-wellbore head and flow profiles of the layers relative to the head and flow profiles of the layers at some radial distance from the wellbore where approximately horizontal radial flow occurs in all layers (Fig. 10B), and accordingly where head contours are approximately vertical (Javandel and Witherspoon, 1969; Molz et al., 1994). With or without skin, the wellbore is essentially a constant-head boundary and the constant pumping rate means the total flux of all layers is constant. Therefore, for wells with positive skin, some redistribution of flow between layers must occur in the near-wellbore region (i.e. in the region between the nearly vertical head contour at the wellbore and the vertical head contours at some radial distance from the wellbore, see Fig. 10B). That is, some flow is diverted from the higher-$K_r$ layers to the lower-$K_r$ layers and the near-wellbore flowfield now includes vertical components with corresponding additional head losses.

Vertical flow diversion, then, is a mechanism that: (a) is associated with positive wellbore skin and a layered aquifer system; (b) can cause head losses at a pumping well larger than predicted with a
homogeneous model; and (c) is not included in the WTAQ analytical model. To estimate the magnitude of such an effect for an aquifer system like that at the BHRS, a series of numerical modeling experiments were run (Fig. 11, Table 4) with: (a) a base case of a homogeneous (one-layer) aquifer; (b) a five-layer aquifer having about one-order of magnitude of range in $K_r$ but the same average $K_r$ as that of the one-layer aquifer base case; and (c) a five-layer aquifer having about two-orders of magnitude of range in $K_r$ but the same average $K_r$ as that of the one-layer aquifer base case. The general geometry and aquifer parameter values used for this modeling are similar to those at the BHRS.

As was the case for the numerical experiments on the partially sand-filled screen (see Section 4.4.1), we use the axisymmetric cylindrical geometry grid configuration in MODFLOW-2000 (Clemo, 2002; Clemo and Barrash, 2003). Test conditions include pumping at 112 L/min in a 15 m thick aquifer in order to compare results with six tests at the BHRS run at 112 ± 2 L/min (Table 3). Three different average $K_r$ values (Table 4) are considered to examine variation similar to what occurs at the BHRS (Fox, in prep.). Results indicate that the additional head loss due to vertical flow diversion between layers near the pumping well caused by positive skin in a 15 m thick, layered system with moderate $K_r$ contrast is on the order of $0.05–0.12$ m (Table 4). If we subtract head loss of this magnitude (i.e. drawdown unaccounted for in WTAQ) from drawdown measured at pumping wells at the BHRS and use the average $K_{s,obs}$ (0.0023 cm/s) to match drawdown curves with WTAQ (i.e. in a single-layer system with the same average $K_r$), then good matches can be obtained for most pumping tests without changing aquifer parameters determined in previous matches at the respective pumping well-observation well pair for most pumping tests (Table 5). For matching these curves, $K_{s,Q}$ is about equal to $K_{s,obs}$.

We have similarly checked to see if the layering effect might cause time-delay differences from a one-layer (equivalent average $K_r$) aquifer at an observation well with wellbore skin. Some delay due to layering is recognizable at nearby observation wells for an ideal pumping system.
but delays are minimal (and hence influences on skin estimates are minimal) for matches to real data where initial pumping rates are variable for the first few seconds before stabilizing.

5.3.2. Possible additional head loss due to radially convergent flow near the pumping well in a heterogeneous system

Desbarats (1992) and Neuman and Orr (1993) have shown that the effective or average $K_r$ at a pumping well in a heterogeneous aquifer (such as that at the BHRS) may appear to be less than the effective or average $K_r$ at an observation well. With the strongly radially convergent flow conditions at a pumping well, flow adjacent to the well must occur through all local low-$K_r$ zones or lenses as well as high-$K_r$ zones to reach the well. In contrast, at some radial distance away from the pumping well, where gradients are not strongly converging, flow passing in the vicinity of an observation well can preferentially follow higher-$K_r$ flow paths (Desbarats, 1992). Rovey and Niemann (2001) note this difference in effective $K_r$ (i.e. geometric mean $K_r$ at observation well > harmonic mean $K_r$ at pumping well) may result in misinterpretation of well tests and they use the term ‘pseudoskin’ for the lower $K_r$ at pumping or slug wells vs observation wells. The pseudoskin effect may explain some additional $K_{s,obs}$ vs $K_{s,Q}$ differences beyond what are caused by layering, but current understanding of the three-dimensional $K_r$ distribution at

<table>
<thead>
<tr>
<th>$K_{s,Q}$ (cm/s)</th>
<th>Average $K_r$ (cm/s)</th>
<th>Number of aquifer layers</th>
<th>$K_r$ range</th>
<th>Drawdown at pumping well (m)</th>
<th>Drawdown difference vs 1-layer model (m)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1</td>
<td>1</td>
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<td>1</td>
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<td>~10</td>
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<td>0.0023</td>
<td>0.09</td>
<td>5</td>
<td>~100</td>
<td>0.454</td>
<td>0.100</td>
</tr>
</tbody>
</table>

Table 4
Modeling data for investigating head loss due to layering and $K_r$ range for a 15 m thick aquifer or aquifer system pumped at 112 L/min

but delays are minimal (and hence influences on skin estimates are minimal) for matches to real data where initial pumping rates are variable for the first few seconds before stabilizing.

5.3.2. Possible additional head loss due to radially convergent flow near the pumping well in a heterogeneous system

Desbarats (1992) and Neuman and Orr (1993) have shown that the effective or average $K_r$ at a pumping well in a heterogeneous aquifer (such as that at the BHRS) may appear to be less than the effective or average $K_r$ at an observation well. With the strongly radially convergent flow conditions at a pumping well, flow adjacent to the well must occur through all local low-$K_r$ zones or lenses as well as high-$K_r$ zones to reach the well. In contrast, at some radial distance away from the pumping well, where gradients are not strongly converging, flow passing in the vicinity of an observation well can preferentially follow higher-$K_r$ flow paths (Desbarats, 1992). Rovey and Niemann (2001) note this difference in effective $K_r$ (i.e. geometric mean $K_r$ at observation well > harmonic mean $K_r$ at pumping well) may result in misinterpretation of well tests and they use the term ‘pseudoskin’ for the lower $K_r$ at pumping or slug wells vs observation wells. The pseudoskin effect may explain some additional $K_{s,obs}$ vs $K_{s,Q}$ differences beyond what are caused by layering, but current understanding of the three-dimensional $K_r$ distribution at

Table 5
$K_{s,Q}$ and $K_{s,obs}$ values from an example set of pumping tests with drawdown at pumping wells adjusted for conceptual model-error due to layering

<table>
<thead>
<tr>
<th>Q well</th>
<th>Obs well</th>
<th>r to obs well (m)</th>
<th>$Q$ (L/min)</th>
<th>$K_{s,Q}$ (cm/s)</th>
<th>$K_{s,obs}$ a (cm/s)</th>
<th>$K_r$ ave (cm/s)</th>
<th>Drawdown difference used for match at pumping well (m)</th>
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<td>113</td>
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<td>0.00195</td>
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<td>0.0023</td>
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<tr>
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<td>0.0023</td>
<td>0.00255</td>
<td>0.075</td>
<td>0.122 b</td>
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<td>0.0021</td>
<td>0.075</td>
<td>0.091</td>
</tr>
</tbody>
</table>

a $K_{s,obs}$ value is the same as was used in original curve match (Table 3).
b Adjustment of drawdown at the pumping well due to the layering effect moves data closer to the type curve with $K_{s,Q}$=0.0023 cm/s, but significantly greater drawdown adjustment or reduced $K_{s,Q}$ is necessary to obtain a match.
the BHRS is insufficient to quantitatively evaluate this effect.

6. Discussion

For aquifers with variation in $K$ of $\sim 1–2$ orders of magnitude in layered systems with positive wellbore skin at pumping wells, a potentially significant fraction of the drawdown at such a pumping well may be due to flow diversion between layers near the wellbore. Our analysis in Section 5 shows that the general magnitude of head loss associated with such flow diversion may be comparable to that occurring for a modest range of $K$ in layered systems that are generally similar to the aquifer system at the BHRS (Tables 4 and 5). This allows, but does not require, that using an approximation of homogeneity (conceptual model-error) is a major cause of the drawdown difference. That is, we now have a rationale for applying fitting adjustments that are sufficient to achieve matches which give a reasonable $K_{s,Q}$ result in most cases, but we do not know if other factors are involved and/or if the amount of drawdown adjustment used is correct.

To this point, we have not considered finer-scale heterogeneity although there is reason to believe that $K$ varies within some layers, as well as between layers, at the BHRS (Barrash and Clemo, 2002; Goldstein et al., 2003; Barrash and Rebollet, 2004). Indeed, variation within layers is expected in natural, high-energy, coarse-grained fluvial deposits (Bluck, 1979; Steel and Thompson, 1983; Dawson and Bryant, 1987) and may also contribute to the ‘pseudoskin’ effect (i.e. additional cause of head loss and apparently lower $K_{s,Q}$ values) associated with radially convergent flow near pumping wells.

In a somewhat similar manner, we assume a constant average $K_s$ but it is likely that $K_s$ will vary to some extent throughout a given well screen. As a first approximation, it is reasonable to assume (as we have done in this paper) that such variations are not great because the screen is everywhere adjacent to sediments with available sand of medium and finer grain sizes. However, we acknowledge that local variations of $K_s$ could enhance or reduce head losses compared to those due to constant average $K_s$.

7. Summary and conclusions

Positive wellbore skin effects were observed in pumping test data from wells that were completed with 10 cm ID, schedule 40, PVC slotted casing in unconsolidated coarse-grained fluvial deposits using a drilling method where: the formation was held back by drive casing; synthetic mud was used; and the formation was allowed to collapse against the well screen upon removal of the drive casing. Residual synthetic drilling mud was decomposed with bleach and drilling fines were removed with surging and pumping, but these treatments did little to reduce the positive skin effect.

Laboratory tests and associated modeling experiments on screen alone and on screen with partial blockage of slots did not generate the magnitude of drawdown attributed to skin during pumping tests. However, numerical modeling experiments and associated field observations of partially sand-filled screen slots are consistent with additional drawdown attributed to skin effects seen in pumping tests at the BHRS in 1999. Step tests demonstrate that non-linear head losses at inflow to well A1 at the BHRS are not apparent at pumping rates $\leq 114$ L/min and so, likely, do not contribute to drawdown measured in most of the 1999 pumping tests.

Analytical modeling of pumping tests at the BHRS after well cleaning (i.e. after dissolution of synthetic drilling mud and removal of residual fines outside the well screen) yields similar $K_{s,\text{obs}}$ values (average $K_{s,\text{obs}} = 0.0023$ cm/s) for nine wells. Skin $K$ values at these wells when they were used as observation wells are less variable and (with one exception) are higher by $\sim 1.5–5$ times compared with $K_{s,Q}$ at the same wells when they were used as pumping wells. After accounting for conceptual model-error due to treating the system as a homogeneous (one-layer) aquifer rather than as a multi-layered aquifer, much or all of the difference may be removed between $K_s$ determined at observation or pumping wells for most tests. Also, the pseudoskin effect due to strongly radially convergent flow at pumping wells in heterogeneous aquifers is another mechanism for additional head loss at pumping wells which, if present, would be incorporated into $K_s$ by default. For the above reasons, modeling analyses of drawdown vs time at observation wells provide better $K_s$ estimates than those from pumping wells in the well-aquifer system at the BHRS.
Acknowledgements

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Appendix A. Laplace transform solution for delayed observation well response including skin effect at the observation well

Here we present the basis for including wellbore skin effects at an observation well in the context of the analytical solution for well and aquifer hydraulics for an axisymmetric, homogeneous system that can be unconfined or confined, isotropic or anisotropic, with pumping and observation wells that can be fully or partially penetrating, and can have finite or infinitesimal diameter (Moench, 1997; Barlow and Moench, 1999). We start with the expression for head and flow balance at the interface between the aquifer and the observation well screen.

\[ \pi r_{\text{obs}}^2 \frac{\partial h_{\text{obs}}}{\partial t} = 2\pi r_{\text{obs}} L \frac{K_s}{d_s} (h - h_{\text{obs}}) \]  \hspace{1cm} (A1)

Next we introduce dimensionless quantities for time and skin at the observation well and then for head in the aquifer and observation well.

\[ t_D = \frac{K_r t}{r_w^2 S_s} \]  \hspace{1cm} (A2)

\[ F_{s,\text{obs}} = \frac{K_r d_s}{r_{\text{obs}} K_s} \]  \hspace{1cm} (A3)

(Eq. (A1)) is revised to maintain a dimensionless system:

\[ \frac{K_r \pi r_{\text{obs}}^2}{r_w^2 S_s} \frac{\partial h_{\text{obs}}}{\partial t_D} = 2\pi L \frac{r_{\text{obs}} K_s}{K_s d_s} (h_D - h_{\text{obs}} D) \]  \hspace{1cm} (A4)

where

\[ h_D = 4\pi K_r b (h_0 - h)/Q \]  \hspace{1cm} (A5)

and

\[ h_{\text{obs}} D = 4\pi K_r b (h_0 - h_{\text{obs}})/Q \]  \hspace{1cm} (A6)

Rearranging (Eq. (A4)) gives

\[ \frac{\pi r_{\text{obs}}^2}{2\pi r_w^2 S_s L} \frac{\partial h_{\text{obs}}}{\partial t_D} = \frac{r_{\text{obs}} K_s}{K_s d_s} (h_D - h_{\text{obs}} D) \]  \hspace{1cm} (A7)

which may be restated as

\[ W_D' F_{s,\text{obs}} \frac{\partial h_{\text{obs}}}{\partial t_D} = h_D - h_{\text{obs}} D \]  \hspace{1cm} (A8)

where

\[ W_D' = \frac{\pi r_{\text{obs}}^2}{2\pi r_w^2 S_s L} \]  \hspace{1cm} (A9)

or as

\[ W_D'' \frac{\partial h_{\text{obs}} D}{\partial t_D} = h_D - h_{\text{obs}} D \]  \hspace{1cm} (A10)

where

\[ W_D'' = W_D' F_{s,\text{obs}} \]  \hspace{1cm} (A11)

(Eq. (A11)) leads to

\[ pW_D'' \tilde{h}_{\text{obs}} D = \tilde{h}_D - \tilde{h}_{\text{obs}} D \]  \hspace{1cm} (A12)

where \( p \) is the Laplace transform variable. And thus, it follows that dimensionless head at the observation well in the Laplace domain is

\[ \tilde{h}_{\text{obs}} D = \frac{\tilde{h}_D}{1 + p W_D''} \]  \hspace{1cm} (A13)

which is of the same form as Eq. (30) of Moench (1997) for dimensionless head in the Laplace domain at the pumping well.

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